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Big Astrophysics in a Small Package
The Gravity & Extreme Magnetism SMEX (GEMS) Mission

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ABSTRACT

The Gravity and Extreme Magnetism SMEX (GEMS) mission will be the first mission to use x-ray polarimetry to characterize the geometry and behavior of x-ray sources, including supermassive black holes and magnetars. Although such astrophysics missions usually require a “large” spacecraft, recent advances in technology allow a smaller spacecraft to conduct significant science in this exciting field. By focusing on the polarization of x-rays, GEMS will enable scientists for the first time to answer some of the most exciting questions in astrophysics. Polarization has the potential to resolve conflicting estimates of black hole spin, reveal how energy is released in this environment, and probe the physics behind strong magnetic fields.

GEMS is made possible by recent breakthroughs in several key technologies. Advances in gas detector technology have enabled exploitation of photoelectric polarimetry, without sacrificing sensitivity. Light-weight mirrors are constructed of especially treated aluminum foils. A deployable boom provides the appropriate separation between the detectors and the mirrors. GEMS has three telescopes on one spacecraft increasing the effective collection area compared to one large telescope. It is the small dimensions and mass of the telescopes and the deployable boom that permits the mounting of three telescopes and vehicle rotation, while retaining a small overall observatory size. Supporting the instrument is the LEOStar 2/750 spacecraft bus.

INTRODUCTION

GEMS was proposed to NASA as part of the Small Explorers (SMEX) 2007 Announcement of Opportunity. GEMS was one mission out of 32 proposals submitted for the SMEX 2007 Announcement of Opportunity, (see **Figure 1** for the GEMS high level schedule). NASA selected GEMS, along with five other SMEX mission proposals to complete a Phase A concept study. NASA is to downselect from the six funded Phase A studies to two missions in July 2009, these two missions will be funded for detailed design through launch and operation (Phase B-F). During the Phase A study the GEMS design was refined and a Concept Study Report (CSR) was submitted to NASA in December 2008, followed by a site visit, where the NASA review panel was hosted at Orbital Sciences Corporation on April 9, 2009. GEMS will follow in a long line of Principal Investigator (PI) led NASA Small Explorer (SMEX) missions which provide frequent flight opportunities for highly focused and relatively inexpensive space science missions, with 8 SMEX missions launched since 1992. The GEMS Principal Investigator is Dr. Jean Swank,

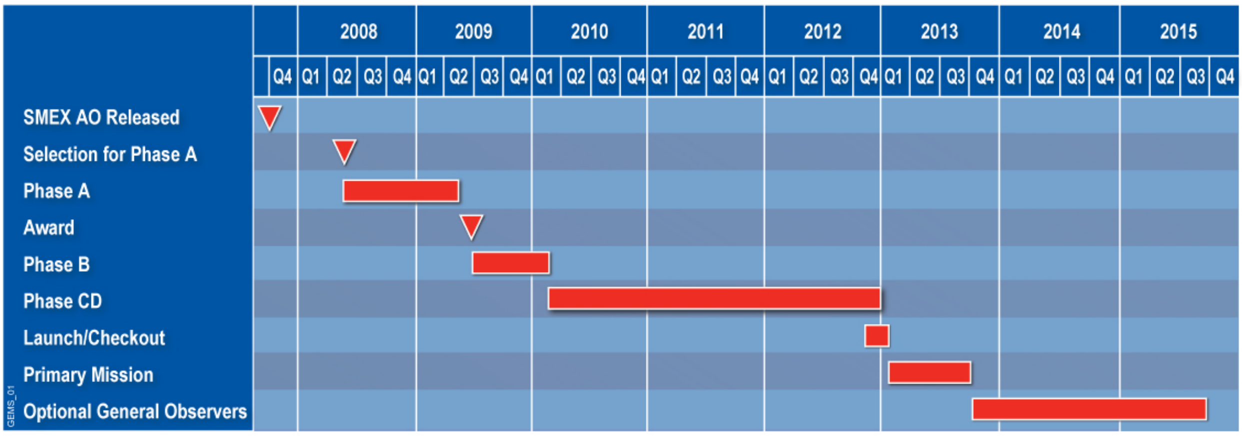

Figure 1: GEMS high-level schedule

who has over 30 years of relevant NASA and astrophysics experience.

GEMS will be launched a Pegasus-class launch vehicle in December 2012. The configuration of the GEMS spacecraft at the time of launch is shown in **Figure 2** below. The launch vehicle will insert the observatory into a 575 km, 28.5 degree inclination, circular, LEO orbit. GEMS will then begin its 30-day checkout, including deployment of the solar arrays, jettison of the mirror covers, and deployment of the 4-meter boom, rotation of the observatory will be initiated and the attitude control system will be checked out. The polarimeters will then be powered on, and the science team will begin checkout of the x-ray Polarimeter Instrument (XPI), by pointing the telescope at known x-ray sources. Following this checkout period GEMS will begin its primary 9 month mission, taking measurements of the 35 prime targets, including stellar black holes, seyfert galaxies and quasars, blazars, a variety of neutron star pulsars, shell supernova remnants and pulsar wind nebulae. Following the baseline mission phase there is an optional operational period whereby general observers can submit targets for study. Adequate mission time for these additional targets will be available as GEMS is designed to meet the two year goal with ample margin.

SCIENCE OBJECTIVES

The GEMS mission will use polarimetry to characterize the geometry and behavior of x-ray sources, including supermassive black holes and magnetars. The polarimeters exploit photoelectric polarimetry which combines broad band width with good polarization sensitivity. A comparison of the sensitivity of photoelectric and scattering polarimeters at the focus of a telescope is presented in Weisskopf (2006, figures 8 and 9)[1]. Further improvements in sensitivity are enabled by the readout geometry employing Time Projection Chambers described by Black (2007)[2], and proposed for GEMS.

The photoelectric polarimeter measures all polarizations simultaneously; since the TPC polarimeter creates images of photoelectron tracks with a combination of fixed pitch readout strips and fixed frequency sampling, it may be difficult to remove all instrumental signatures. The payload thus requires rotation about the science

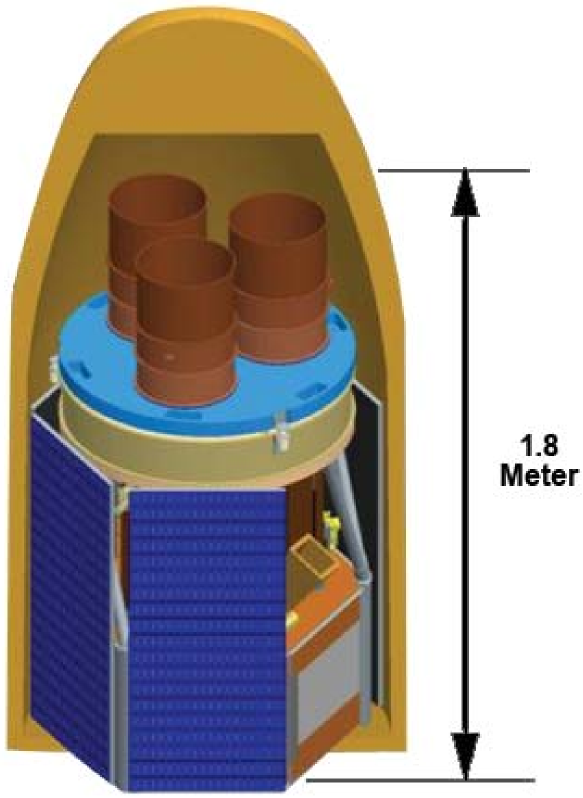

Figure 2: GEMS observatory in stowed configuration

axis which causes all sky angles to be sampled at all detector angles.

Most microphysical processes affecting x-rays, including scattering and magnetic emission processes, are polarization-dependent. Most cosmic X-Ray sources should produce polarized radiation. Observations of polarization provide a measure of the geometrical distribution of gas and magnetic fields, and x-ray polarization is in most cases essentially free of the foreground depolarization that affects longer wavelengths. X-ray polarization is also sensitive to exotic physical processes occurring in regions of very strong gravity and magnetic fields. General relativity predicts that the plane of polarization of photons propagating close to black holes is rotated by an amount that depends on the proximity to the hole and its spin. In passing through a region of very high magnetic field, photons interact not only with electrons, but also with the virtual electrons and positrons present in the vacuum described by quantum electrodynamics. GEMS observations of x-ray polarization will test the understanding of fundamental physics under such extreme conditions.

Polarimetry contains information about emission mechanisms that imaging alone cannot provide. Two of the most common x-ray radiation mechanisms, Compton scattering (**Figure 3)** and synchrotron radiation (**Figure 4)**, create strong polarization that carries powerful diagnostic information. In the case of Compton scattering, very large polarization fractions can be achieved when the scattering angle is near 90 degrees. In these circumstances, the polarization direction is tied tightly to the geometry of the source. Synchrotron radiation can likewise produce fractional polarization at the tens of percent level (up to 70% for a uniform source), with its magnitude dependent on the shape of the electron distribution function, and its direction revealing the orientation of the mean magnetic field in the source.

With the breakthrough technology made in the area of Micropattern Gas Detectors (MPGDs) and use of Time Projection Chambers (TPCs), the GEMS mission will enable scientists for the first time to answer some of NASA's most exciting questions in astrophysics, such as:

- How does black hole spin affect space-time and matter as it is accreted in strong gravity?
- Where is the magnetic energy released near black holes?
- What are the radiation mechanisms in blazars?
- Are x-rays from obscured (Seyfert 2) Active Galactic Nuclei (AGN) scattered around the obscuration?
- Was the Galactic Center black hole much more luminous in the recent past than it is today?
- What happens in the superstrong magnetic fields near pulsars and magnetars?
- What is the origin of the x-ray emission from rotationally-powered pulsars?
- What is the magnetic field structure of accretion-powered x-ray pulsars?
- How does cosmic ray acceleration occur in supernova remnants?
- How ordered are the magnetic fields of pulsar wind nebulae?

Black holes radiate across the electromagnetic spectrum, from radio to gamma-rays, and the different wavelengths convey different insights. Both timing and spectral measurements of these objects have been obtained with the full breadth of NASA missions: Hubble Space Telescope (HST) in the optical; Spitzer in the infrared (IR); Rossi X-ray Timing Explorer (RXTE), Chandra, XMM-Newton and Suzaku in the x-ray. Despite this, interpretation of the results in terms of fundamental parameters of the black hole, such as its spin, still remains model-dependent. GEMS'

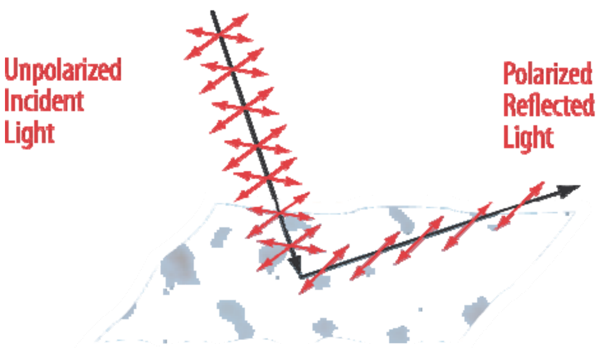

Figure 3: Scattering induces polarization

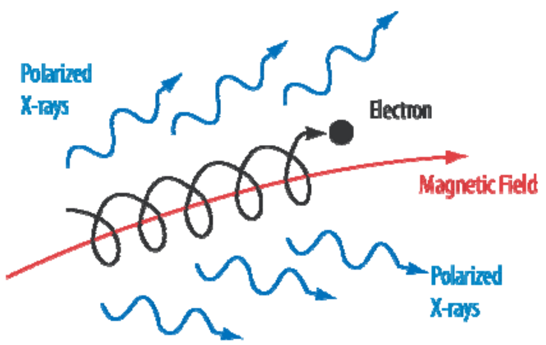

Figure 4: Synchrotron emission in a strong magnetic field

polarimetry information will provide a key piece that has been missing from the puzzle, and narrow the search for the true model. GEMS' results will thus enrich the value of much larger current and future missions.

PAYLOAD

The GEMS main science payload, the X-ray Polarimeter Instrument (XPI), consists of three co-aligned telescopes. Each telescope has a high throughput, high heritage, grazing incidence mirror that focuses x-rays onto a high efficiency polarimeter that measures the polarization-dependent direction of the initial photoelectron using a time projection technique. The mirrors are near copies of the mirrors employed on the Suzaku mission[3]. One telescope includes the Student Collaboration experiment, the Bragg Reflection Polarimeter (BRP), which extends GEMS' baseline capabilities.

The three mirrors are mounted on a common Mirror Optical Bench (MOB), which the three polarimeter detectors are mounted on an Instrument Support Structure (ISS). The Telescope Optical Boom (TOB) connects the MOB and ISS. The TOB, which is stowed for launch, undergoes a one-time on-orbit deployment that places the mirrors 4.5 m in front of the detector mid-points. **Figure 5** shows the payload in its deployed state.

In order to accomplish this mission, a new six sided boom design was needed in order to satisfy the mission objectives and fit into a Pegasus class launch vehicle. Using an existing boom design would have required a larger volume, and hence a larger launch vehicle. A design of the boom was implemented for a two thirds scale engineering demonstration unit and is successful in stowing and deploying. An engineering test unit will be implement which will be used to test the accuracy and repeatability of the deployment.

SPACECRAFT

The GEMS S/C is the LEOStar-2/750 platform, an evolution of the Orbital Sciences Corporation LEOStar-2 product line, with a single-box avionics suite, the Master Avionics Unit (MAU). The fully deployed GEMS observatory is shown in **Figure 6**.

A robust, stable, three-axis Attitude Control Subsystem (ACS) relies on a two-headed Danish Technical University (DTU) Advanced Stellar Compass (ASC) star tracker to provide attitude data, a LN200+ gyro to provide rate data, and eight cosine sun sensors to provide a coarse sun vector. Four reaction wheels control the attitude and three magnetic torque rods unload momentum. The bus structure consists of aluminum facesheet over aluminum honeycomb panels. GEMS includes a deployed single axis gimbaled solar array wing, which must be counter rotated at a 0.1 rpm rate to track the sun. The 30 A-hr AEA Battery Systems Ltd. (ABSL) Li-ion battery is sized for worst case eclipses and anomaly conditions.

The MAU avionics is a straightforward enhancement of the spacecraft avionics developed by SEAKR Engineering for the Air Force Research Laboratory (AFRL) Demonstration and Science Experiments (DSX) program. This enhancement was funded by Orbital and SEAKR beginning in 2005. The MAU is based on a flight-heritage 3U RAD-750 processor card and accommodates all C&DH and power electronics functions. Four standard RS-422, discrete, and analog interfaces connect the MAU with the payload and the bus components. Command sequences can be either stored or executed in real-time. The FSW achieves high reusability and in-flight flexibility through a table-based design. The S-band communications system supports data downlinks and critical event monitoring through the Tracking and Data Relay Satellite System (TDRSS).

The LEOStar2/750 spacecraft is primarily a single string with several fault management and reliability-enhancing features, including the following selective redundancy features:

- Four small reaction wheels for a mission that can be accomplished with three.
- DTU star tracker, with dual optical heads

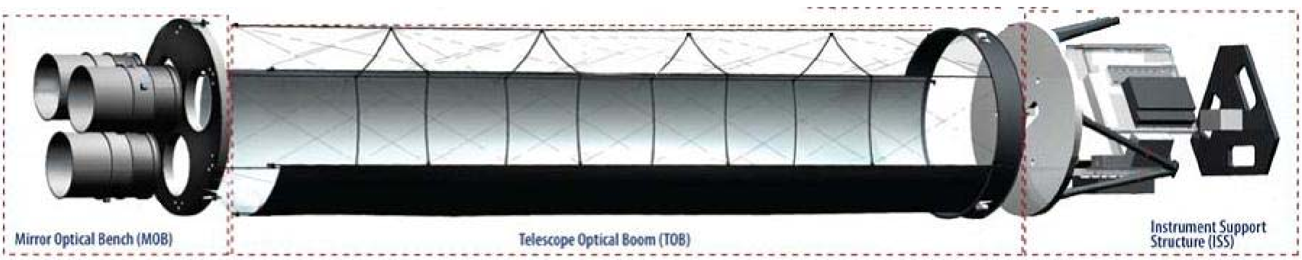

Figure 5: GEMS Payload in its deployed configuration

- Independent RS-422, power, and 1 pulse-per second (PPS) timing interface that connect to each of the three polarimeters and the Bragg Reflection Polarimeter (BRP).

MISSION OPERATIONS

GEMS mission operations uses simple and robust operational concept. It features once a day downlink and a once a week uplink, utilizes existing facilities, processes, procedures and ground system located at Orbital Sciences Corporation in Dulles, VA for the Mission Operations Center (MOC), along with an existing Science Operations Center (SOC) at Goddard Space Flight Center . Spacecraft communication contacts are carried out through the Universal Space Network. A depiction of the operational concept can be seen in **Figure 7**.

After the 30-day checkout is complete, the GEMS baseline operational phase continues for nine months. During this time, GEMS measures the polarization of x-ray emissions from cosmic x-ray sources spanning about three orders of magnitude in brightness. Observation durations are calculated to produce useful limits on the polarization of the x-ray flux. Observations last from hours to weeks depending on the brightness of the source. The observatory rotates at 0.1 rpm to measure and remove systematic errors in the polarization measurements. Targets are chosen within a 60° band normal to the sun to maintain a worst-case 30° sun incidence angle to the solar array. Measurements do not take place during parts of the orbit when the target is occulted behind the Earth or the observatory passes through the South Atlantic Anomaly (SAA), resulting in an estimated 50% observing efficiency.

CONCLUSIONS

Advances in instrument and spacecraft technology are making it possible to fly very significant capability in the envelop of a "small" mission, one of NASA's Small Explorers, which is required to be compatible with a Pegasus launch vehicle. A Pegasus fairing can fit x-ray telescopes that nearly fill the cross sectional area for minimal mass. Detectors can be maximized for efficiency while keeping the sensitivity high. Miniaturization of computers and parts makes it realistic to minimize the mass of separate components, for example in the MAU. The mission has power capability to allow rotation of the bus and instrument together and pointing with a 30 degree offset from the sun.

This mission will be able to observe dozens of sources distributed around the sky. GEMS will prove the effectiveness of x-ray polarization as a new tool to probe x-ray sources. It will have a large impact on astrophysics, opening a new field.

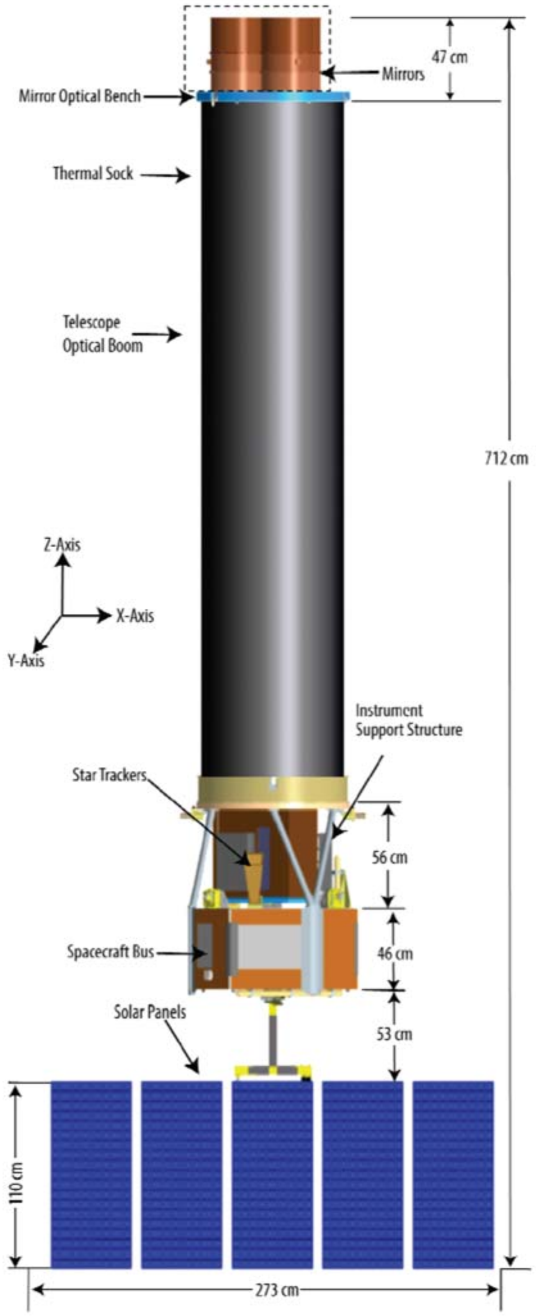

Figure 6: GEMS Observatory in deployed configuration

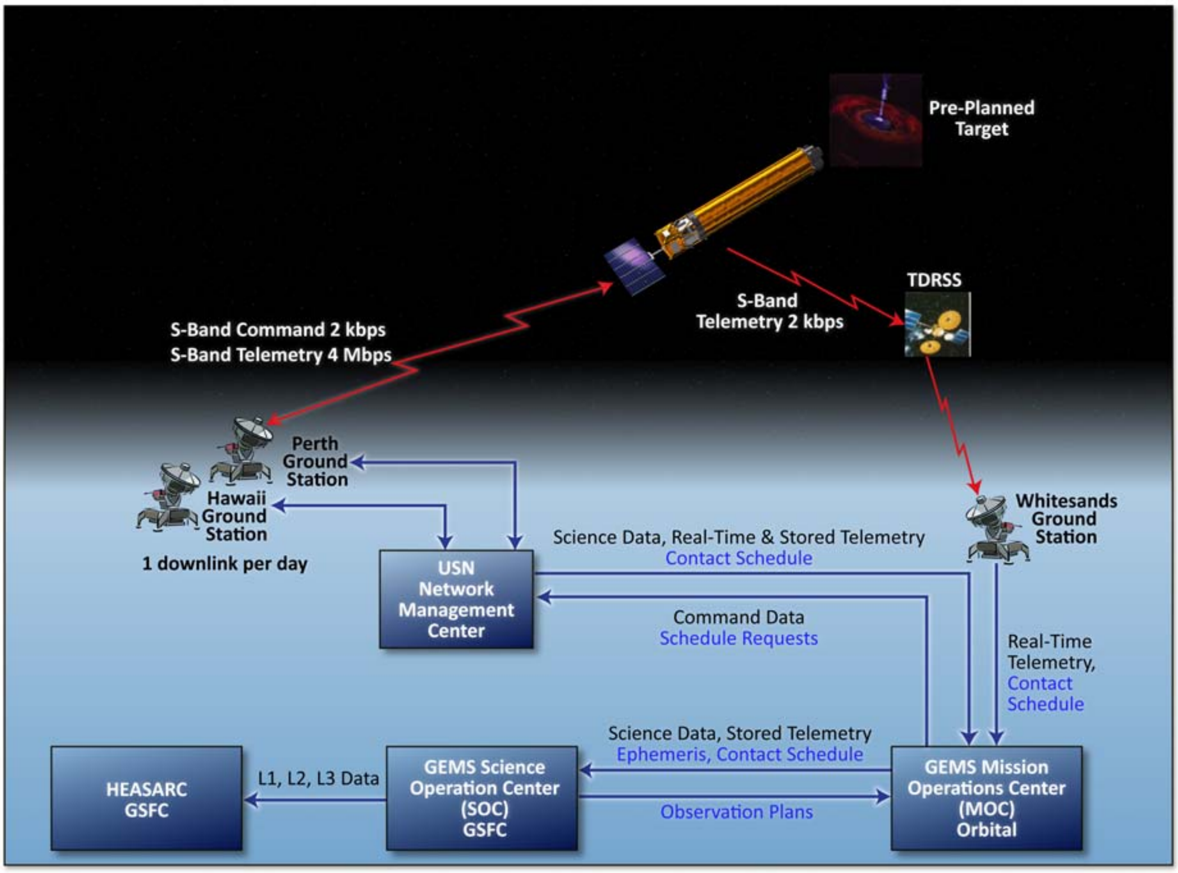

Figure 7: GEMS Mission Operations Concept

ACKNOWLEDGEMENTS

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